Suspended Sediment and Seabed Modifications Driven by Energetic Waves and a Strong Coastal Current

Courtney K. Harris
Virginia Institute of Marine Science
P.O. Box 1346 (Mailing)
Route 1208, Greate Road (Shipping)
Gloucester Point, VA 23062
phone: (804)684-7194; fax: (804)684-7198; email: ckharris@vims.edu

Award Number: N00014-04-1-0222
http://www.vims.edu/~ckharris

LONG-TERM GOALS

Estimates of sediment concentrations and flux in coastal oceans can help predict optical and acoustical water properties, interpret remotely sensed coastal data, and characterize seafloor morphology. Predicting turbidity requires that we account for processes that erode, supply, and redistribute sediment; including storms, floods, winds, tides, and energetic waves. In many environments, particularly estuaries and offshore of river mouths, doing so requires that we consider both horizontal and vertical flux gradients. Including advances in sediment transport dynamics and bottom boundary layer structure within three-dimensional transport models should improve our ability to predict turbidity, sediment flux, and erosion and deposition.

OBJECTIVES

Quantifying sediment fluxes is particularly challenging near river mouths, where buoyant plume dynamics and terrestrially derived sediment influence transport and resuspension. In areas with strong coastal currents, freshwater plumes can impact currents for hundreds of kilometers. One- and two-dimensional models that work well on open continental shelves represent poorly areas offshore of river mouths, which are inherently three-dimensional. They also fail in areas of strong coastal currents because they neglect upstream sources. Three-dimensional hydrodynamic models, however, provide a promising platform within which to predict sediment suspension and transport in such areas because they account for advection and plume dynamics.

We improved a three-dimensional sediment transport model and tested it using data gathered in the Adriatic Sea from the Fall, 2002 – Spring, 2003 (figure 1). We also used the model to evaluate whether water column turbidity and flux depends more on spatial patterns in waves, currents, fluvial discharge, or sediment properties. By developing a numerical model that includes predictions of fluvial input, wave-current resuspension, and advection by ocean currents we attempted to include the primary contributions to water column turbidity. For direct comparison to field data, calculations of ocean currents and sediment concentrations must be obtained for the time and place of interest using realistic winds, freshwater input, and wave fields. Because forcing data is rarely available at the temporal and spatial scales necessary, the sediment transport model requires an ensemble approach that includes models of winds and waves [see *Sherwood et al.*, 2004].

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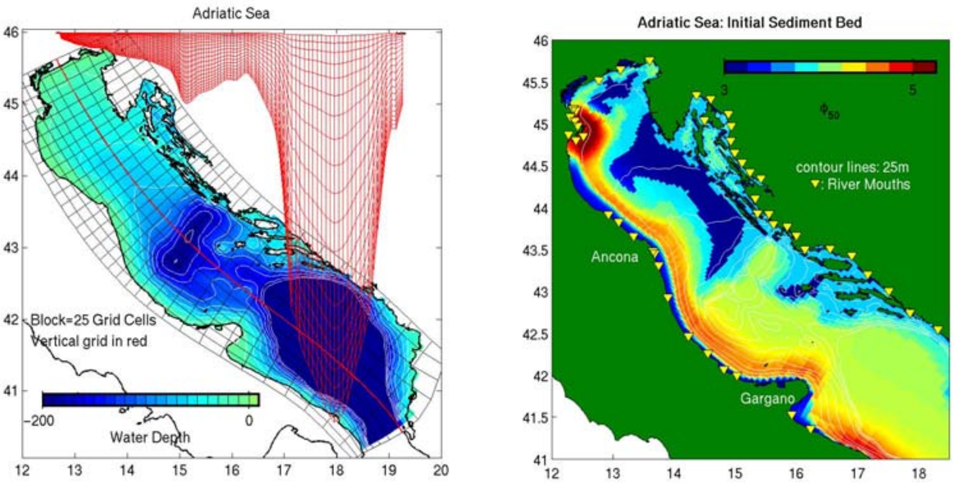

Figure 1: Adriatic Sea grid shown in Panel A, and locations of Po River delta, Ancona, and Gargano Peninsulas in Panel B. Each horizontal grid cell in A represents 25 model grids. Panel B provides the location of freshwater sources included, and bathymetric contours at 25m intervals. Color represents initial sediment size in phi units, based on available grain size data.

APPROACH

The Adriatic Sea was an excellent test bed for refining and testing three-dimensional models of sediment transport and hydrodynamics. As a semi-enclosed sea, sediment and physical oceanographic fields respond to winds and freshwater inputs that are both fairly local and well understood. Additionally, several ONR and NRL funded efforts, including Eurostrataform, ACE, and Dolce Vita; concentrated on the Adriatic Sea during 2002 and 2003, resulting in an impressive data set with which to compare the model [*Lee et al.*, 2005; *Nittrouer et al.*, 2004]. The representation of conditions within the Adriatic Sea was developed in collaboration with scientists at the US Geological Survey (Chris Sherwood, Rich Signell, and John Warner). We used the ROMS (Regional Ocean Modeling System) numerical model [*Haidvogel and Beckmann*, 1999; *Warner et al.*, 2007]. Wave input files were provided by Sherwood and Signell, who ran the SWAN (Simulating Waves Nearshore) model [*Booij et al.*, 1999]. Winds were specified using predictions from two atmospheric models: the 4km-resolution Naval Research Laboratories COAMPS™ model (Coupled Ocean Atmospheric Mesoscale Prediction System); [see *Hodur*, 1997; *Hodur et al.*, 2001]; and 7 km predictions of LAMI (Limited Area Model, Italy, see http://www.cmirl.ge.infn.it/MAP/BOLAM/Bolamin.htm).

We improved model input, focused on the Po River delta, and evaluated the model. The structure of the Western Adriatic Coastal Current (WACC) and sediment dynamics depend on supplies of buoyancy and fine-grained sediment. Using available data we improved inputs of sediment and river discharge to the ROMS model. To better predict plume and coastal current behavior, and to facilitate model validation, we increased resolution to ~0.75 km near the Po River delta.

WORK COMPLETED

We improved the model's specification of freshwater and sediment inputs, increased model resolution near the Po River delta, and developed a snapshot of modern day sediments for use as an initial sediment bed. The model of the Po Delta region was compared to data from the PASTA (Po and

Apennine Sediment Transport and Accumulation) experiment [*Bever and Harris*, 2006]. For a student thesis, a higher resolution (~0.75 km) model of sediment transport and hydrodynamic calculations was completed in the vicinity of Eurostrataform measurements near the Po delta to better represent the structure of the buoyant plume and related sediment depocenters [*Bever*, 2006].

Comparison between model results and data obtained from the Fall, 2002 – Spring, 2003 required that we use reasonably accurate fluvial inputs and sediment properties. Fox et al. [2004] and Mikkelson et al. [2005] observed that sediment settles much more quickly from the mouth of the Po River than it appears to settle from the smaller, Apennine sources. They conclude that Po River sediment is flocculated within the river itself, to a much greater extent than sediment within the Apennine rivers. We therefore usually specify that 90% of the Po River sediment is delivered as fast settling flocs (ws = 0.1 cm/s) whereas 90% of the Apennine sediment is delivered as slowly settling disaggregated particles (ws = 0.01 cm/s). Comparison of model calculations with field observations, however, indicated that sediment resuspended from the bed seemed to behave more like partially consolidated and flocculated material than unconsolidated fines. We therefore assigned all of the silts and clays on the sediment bed critical shear stresses and settling velocities representative of such particles (τcr = 0.1 Pa, ws = 0.1 cm/s). Similar comparisons between the modeled size of the flood deposit and observed deposit thicknesses indicated that the rating curve for the Po River may overestimate sediment supply during this event. Numerical experiments were performed that decreased the rating curve until good agreement was obtained between the modeled and observed flood deposit thickness.

RESULTS

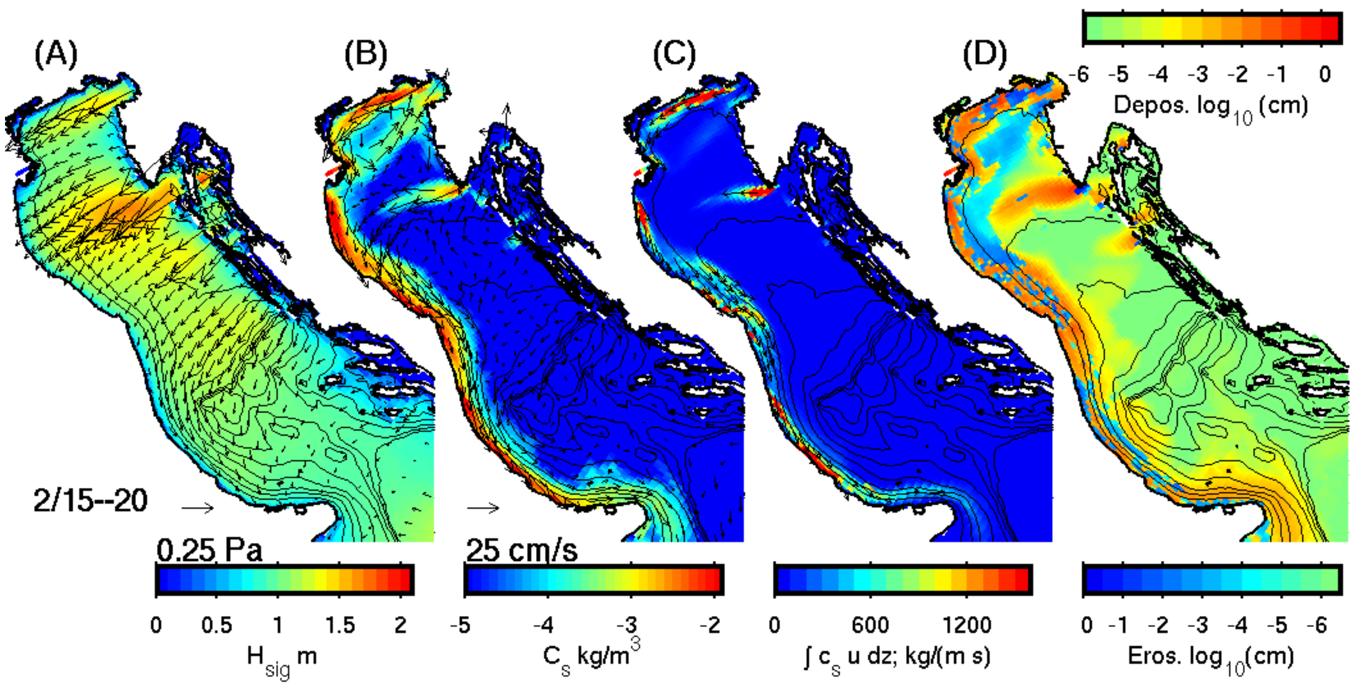

Figure 2: Typical Bora conditions. (A)Wave height (color) and wind stress (arrows). (B) Depth-averaged suspended sediment concentrations (color) and currents (arrows). (C) Depth-integrated sediment flux. (D) Net erosion (blue) and deposition (red) in log-scale. Panels are time-integrated or averaged from February 15 – 20, 2003.

Sediment settling velocity and winds both influenced predictions of water column turbidity within the northwestern Adriatic. Sediment that remained suspended at the Po River mouth was almost all in the disaggregated size class that settled at ws = 0.01 cm/s. Flocculated material, that made up the majority of Po River sediment load [*Fox et al.*, 2004], settled to the seabed within a few kilometers of the river mouth. Two wind regimes dominated sediment dispersal within the Adriatic. Strong storm winds from the northeast, called Bora winds, created large waves along the Italian coast and strengthened the WACC. Numerical modeling efforts and bottom-boundary layer observations showed interesting spatial patterns for the February Bora [figure 2, *Lee et al.*, 2005]. Counter-clockwise gyres were present over the mid-, central- and northern Adriatic (figure 2B), but the majority of sediment transport was to the south. Because Bora conditions strengthened the WACC along the Apennine shelf, they enhanced southward transport there (figure 2C, D). Another wind regime important for sediment transport, Scirroco winds, were less energetic, but often persistent and from the south. Though these were associated with maximum wave energies during the 2002 / 2003 field season, they often resulted in lowered sediment flux because they reduce currents in the WACC.

Comparison of model predictions during the 2002 / 2003 field season to seabed data and water column suspended sediment measurements indicated that the model captured to the first order sediment transport in this area. Deposition near the Po occured at the mouths of the river distributaries, as was observed for a large flood during December, 2002 (figure 3). Deposition in the model, however, overpredicted actual deposit thickness, until the fluvial input term was lowered by decreasing the rating curve, and the fraction of fluvial sediment assumed to be unflocculated was increased to 50%. This result implies that perhaps the rating curve, based on historical sediment data, overpredicts sediment output of the modern Po, as has been argued by others [*Friedrichs and Scully*, 2006]. Additionally, the model neglected disaggregation of particles within the coastal ocean, which may have been compensated for by lowering the fraction of flocculated sediments input by the Po.

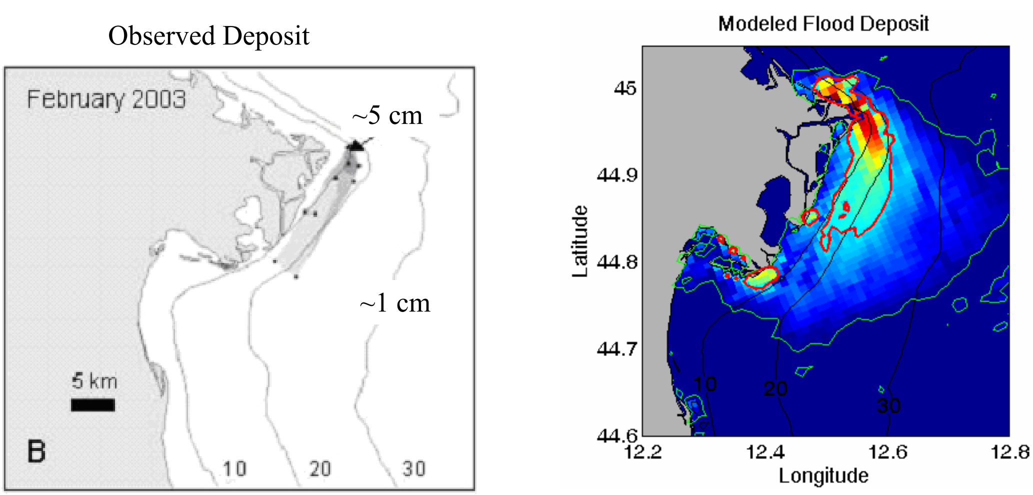

Figure 3: Observed (A) flood deposit from Palinkas et al. (2005). Modeled (B) deposit shown on a log10 scale, assuming a porosity of ~0.7. Deposit thickness ranges from 30-0.005 cm. The deposit that could be observed (0.5 cm) is contoured in red; 0.005 cm is contoured in green.

Near-bed suspended sediment concentrations compared favorably to those observed by Traykovski et al. [2006, in press] being within a factor of 2-3. The modeled suspended sediments profile agreed with tripod observations when resuspended sediments were treated as partially consolidated fines

(figure 4), which was consistent with sediment properties used by a one-dimensional model applied to the same location by Traykovski et al., [2006, in press]. The model identified the correct resuspension events, though it overestimated suspended sediment concentrations, particularly during December, 2002. Current velocities were also overestimated, most likely because the LAMI model did not correctly represent winds nearshore (figure 5). This may explain the overprediction of vertical mixing and sediment flux. We conclude that the sediment model does a reasonable job of predicting suspended sediment concentrations. Its use is limited, however, by the need to know, with a high degree of accuracy, the properties of the waves that resuspend sediment, and the winds that drive currents. Within our study, the wind and wave fields are better prescribed than in many situations, but still appear to introduce large errors in the sediment transport calculations at the nearshore site examined.

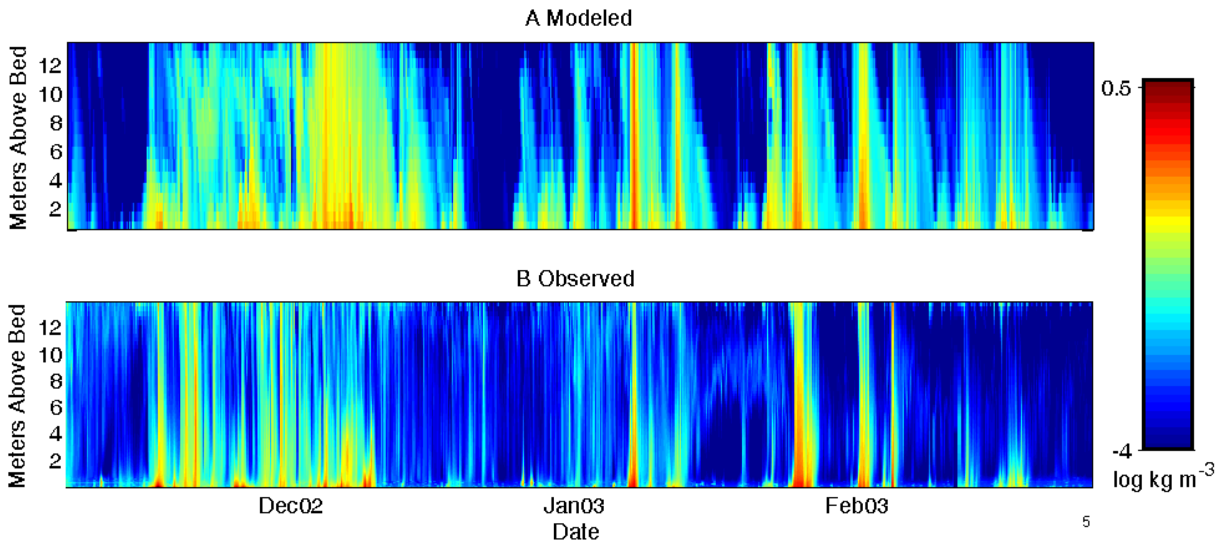

Figure 4: (A) Predicted suspended sediment compared to (B) observed concentrations by Traykovski et al. [2006, in press] at a site located south of the Po delta in 14 m of water.

IMPACT / APPLICATIONS

Our efforts have been part of a group that includes scientists within Eurostrataform, the Adriatic Current Experiment (ACE), DOLCE VITA, and Italian researchers within CNR. ROMS, in particular, has served as a community model, with researchers from VIMS, the US Geological Survey, and CNR trading source code and forcing files. By running the Adriatic implementation of the ROMS-Sediment model, we have uncovered bugs in the developing code and thereby made the community sediment model more robust. VIMS provided the 2 km resolution bathymetry file, initial sediment bed, and river forcing files that include sediment and freshwater to allied researchers. We have also contributed towards efforts to understand deep water formation and air/sea interaction by working to include freshwater terms that improved agreement seen between mid-basin model predictions and data, far from our field of interest along the Italian coastline.

RELATED PROJECTS

Related to this study, I have contributed towards two chapters of a volume on continental-margin sedimentation [*Syvitski et al.*, 2007; *Wheatcroft et al.*, 2007].

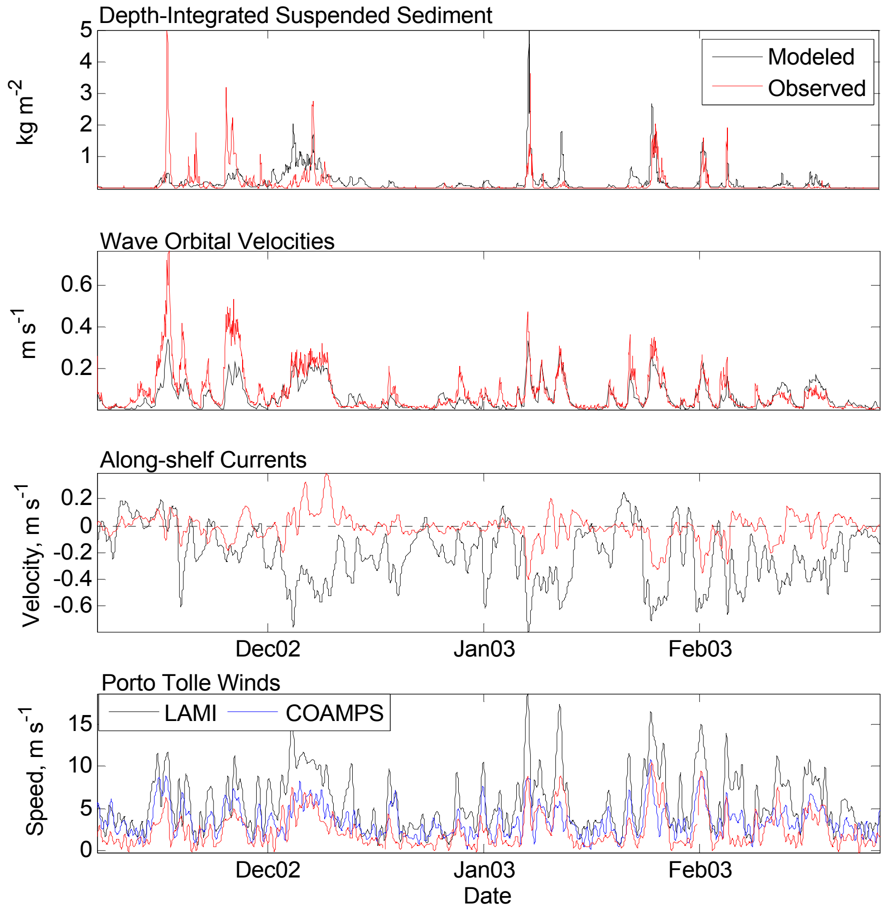

Figure 5: Comparison of model estimates to tripod observations for depth integrated suspended sediment concentration (A); wave orbital velocity (B); along-shelf current speed (C); and a comparison of LAMI, COAMPS, and observed winds over the Po delta (D).

REFERENCES

Bever, A., Physical processes behind delta propagation and flood layer dynamics: Po River, Italy, M.S. thesis, College of William and Mary, Gloucester Point, Virginia, 2006.

Bever, A., and C.K. Harris, Sediment transport off the Po River: a model - data comparison, in *Physics of Estuaries and Coastal Seas (PECS)*, edited by D. Jay, and P. MacCready, pp. in Preparation, Astoria, Oregon, 2006.

Booij, N., R.C. Ris, and L.H. Holthuijsen, A third-generation wave model for coastal regions. Part I - Model description and validation, *Journal of Geophysical Research*, *104* (C4), 7649-7666, 1999.

Fox, J.M., P.S. Hill, T.G. Milligan, and A. Boldrin, Flocculation and sedimentation on the Po River Delta, *Marine Geology*, *203*, 95-107, 2004.

Friedrichs, C.T., and M.E. Scully, Modeling deposition by wave-supported gravity flows on the Po River prodelta: from seasonal floods to prograding clinoforms, *Continental Shelf Research*, *in press*, 2006.

Haidvogel, D.B., and A. Beckmann, *Numerical Ocean Circulation Modeling*, 318 pp., Imperial College Press, London, 1999.

Hodur, R.M., The Naval Research Laboratory's Coupled Ocean / Atmosphere Mesoscale Prediction System (COAMPS), *Monthly Weather Review*, *125* (7), 1414-1430, 1997.

Hodur, R.M., J. Pullen, J. Cummings, X. Hong, J.D. Doyle, P. Martin, and M.A. Rennick, The Coupled Ocean / Atmosphere Mesoscale Prediction System (COAMPS), *Oceanography*, *15*, 88-98, 2001.

Lee, C., F. Askari, J. Book, S. Carniel, B. Cushman-Roisin, C. Dorman, J. Doyle, P. Flament, C.K. Harris, B.H. Jones, M. Kuzmic, P. Martin, A. Ogston, O. Orlic, H. Perkins, P. Poulain, J. Pullen, A. Russo, C. Sherwood, R.P. Signell, and T.D. Detweiler, Transport Pathways of the Adriatic: Multi-Disciplinary Perspectives on a Wintertime Bora Wind Event, *Eos, Transactions, American Geophysical Union*, *86* (16), 157, 163, 165, 2005.

Mikkelsen, O., T. Milligan, P. Hill, and R. Chant, In situ particle size distributions and volume concentrations from a LISST-100 laser particle sizer and a digital floc camera, *Continental Shelf Research*, *25* (16), 1959 - 1978, 2005.

Nittrouer, C.A., S. Miserocchi, and F. Trincardi, The PASTA Project: Investigation of Po and Apennine Sediment Transport and Accumulation, *Oceanography*, *17*, 46 - 57, 2004.

Sherwood, C.R., S. Carniel, L. Cavaleri, J. Chiggiato, H. Das, J. Doyle, C.K. Harris, A. Niedoroda, J. Pullen, C.W. Reed, A. Russo, M. Sclavo, R.P. Signell, P. Traykovski, and J.C. Warner, Sediment dynamics in the Adriatic Sea investigated with coupled models, *Oceanography*, *17* (4), 58-69, 2004.

Syvitski, J.P.M., L. Pratson, P.L. Wiberg, M. Steckler, M. Garcia, W.R. Geyer, C.K. Harris, E. Hutton, J. Imran, H. Lee, M. Morehead, and G. Parker, Prediction of margin stratigraphy, in *Continental-Margin Sedimentation: Transport to Sequence*, edited by C.A. Nittrouer, pp. Chapter XI; in press, Blackwell Press, 2007.

Traykovski, P., P.L. Wiberg, and W.R. Geyer, Observations and modeling of wave-supported sediment gravity flows on the Po prodelta and comparison to prior observations from the Eel shelf, *Continental Shelf Research*, *NA* (NA), NA, 2006, in press.

Warner, J.C., C. Sherwood, R.P. Signell, C.K. Harris, and H.G. Arango, Development of a three-dimensional regional coupled wave-current-sediment transport model, *Computers & Geosciences*, *in review*, 2007.

Wheatcroft, R.A., P.L. Wiberg, C.R. Alexander, S.J. Bentley, D.E. Drake, C.K. Harris, and A. Ogston, Post-depositional alteration and preservation of strata, in *Continental-Margin Sedimentation: Transport to Sequence*, edited by C.A. Nittrouer, pp. Chapter III; in press, Blackwell Publishers, 2007.

PUBLICATIONS

Bever, A., Physical processes behind delta propagation and flood layer dynamics: Po River, Italy, M.S. thesis, College of William and Mary, Gloucester Point, Virginia, 2006. [published]

Harris, C.K., C.R. Sherwood, R.P. Signell, A. Bever, and J.C. Warner. Dispersal of sediment in the Adriatic Sea. In Review for the *Journal of Geophysical Research*.

Harris, C.K., P.A. Traykovski, and W.R. Geyer. 2004. Including a near-bed turbid layer in a three dimensional sediment transport model with application to the Eel River shelf, northern California. *Proceedings of the Eighth Conference on Estuarine and Coastal Modeling.* M.L. Spaulding, et al. (editors), American Society of Civil Engineers. 784—803. [published, refereed]

Harris, C.K., P.A. Traykovski, and W.R Geyer. 2005. Flood dispersal and deposition on the northern California shelf by near-bed gravitational sediment flows and oceanographic transport. *Journal of Geophysical Research*, 110(C09025): d0i: 10.1029 / 2004JC002727 [published, refereed].

Lee, C.M., F. Askari, J. Book, S. Carniel, B. Cushman-Roisin, C. Dorman, J. Doyle, P. Flament, C.K. Harris, B.H. Jones, M. Kuzmic, P. Martin, A. Ogston, M. Orlic, H. Perkins, P. Poulain, J. Pullen, A. Russo, C. Sherwood, R.P. Signell, D. T. Detweiler. 2005. Northern Adriatic response to a wintertime Bora wind event, *EOS, Transactions of the American Geophysical Union*, 86(16): 157, 163, 165 [published, refereed].

Sherwood, C.R., S. Carniel, L. Cavaleri, J. Chiggiato, H. Das, J.D. Doyle, C.K. Harris, A.W. Neidoroda, J. Pullen, C.W. Reed, N. Russo, R.P. Signell, P. Traykovski, J.C. Warner. 2004. Sediment dynamics in the Adriatic Sea investigated with coupled models. *Oceanography,* 17(4): 58-69. [published, refereed].

Syvitski, J.P.M., L. Pratson, P.L. Wiberg, M. Steckler, M. Garcia, W.R. Geyer, C.K. Harris, E. Hutton, J. Imran, H. Lee, M. Morehead, and G. Parker, Prediction of margin stratigraphy, Chapter XI in *Continental-Margin Sedimentation: Transport to Sequence*, edited by C.A. Nittrouer, 2005. [in press, refereed].

Warner, J.C., C.R. Sherwood, R.P. Signell, C.K. Harris, and H. Arango. Development of a three-dimensional, regional, coupled wave-, current-, and sediment-transport model. In Review for *Computers and Geosciences*.

Wheatcroft, R.A., P.L. Wiberg, C.R. Alexander, S.J. Bentley, D.E. Drake, C.K. Harris, and A. Ogston, Post-depositional alteration and preservation of strata, Chapter III in *Continental-Margin Sedimentation: Transport to Sequence*, edited by C.A. Nittrouer, 2005. [in press, refereed].

Wheatcroft, R.A., P.L. Wiberg, C.R. Alexander, S.J. Bentley, D.E. Drake, C.K. Harris, and A. Ogston, Post-depositional alteration and preservation of strata, Chapter III in *Continental-Margin Sedimentation: Transport to Sequence*, edited by C.A. Nittrouer, 2005. [in press, refereed].